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others must remain invisible, until the power of our telescopes is still further increased.

From the average brightness of comets at unit geocentric distance the maximum perihelion distance at which a comet may be seen in opposition from the Earth with the more powerful instruments may be derived. The values of the eccentricity corresponding to this maximum for a given value of the semi-major axis or period will then be the minimum eccentricity which the orbit of a comet of average brightness and of given period must have in order to be visible from the Earth, under the most favorable circumstances.

This question will be studied in connection with a proposed further study of comet orbits. The theory that, in general, comets are permanent members of our solar system seems to have been greatly strengthened by the foregoing preliminary statistics. It will be remembered that until KEELER began photographing nebulæ with the Crossley reflector the spiral was considered the exceptional form of a nebula. The percentage of double stars is increasing so rapidly that their discovery either directly, or spectroscopically, or photometrically, or otherwise, is no longer a cause for surprise. It seems eminently probable that with further investigation of cometary orbits the parabola will be found to be the exception.

BERKELEY ASTRONOMICAL DEPARTMENT, March 30, 1907.

THE SOLAR CORONA.[1]

By W. W. CAMPBELL.

Of all the wonders of this and other worlds that it has been my good fortune to see, a total solar eclipse is by far the most impressive, and the Sun's corona is its central and most beautiful feature. The corona appears to have attracted the attention of intelligent observers who dwelt within the shadow-paths, in all ages of our civilization. PLUTARCH has left an excellent description of its appearance, and occasional later writers have referred to it. Speculation as to what the corona really is was naturally very meager prior to the middle of the last century, for the custom of dispatching expeditions to study eclipse phenomena had not been inaugurated, and it therefore seldom fell to the lot of any one man to observe two eclipses, either with or without scientific instruments and methods.

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[1] Lecture delivered before the Astronomical Society of the Pacific on January 28, 1907. The lantern slide illustrations are necessarily omitted.

In KEPLER'S day, and until less than a century ago, the corona was believed by most men of science to be due to the illumination of the Moon's atmosphere. When it was finally established that the Moon has extremely little or no atmosphere, the corona was generally explained as a phenomenon of the Earth's atmosphere; and it was not until the year 1870 that the tide of scientific opinion turned toward the Sun itself as the origin and center of the corona. Even as late as 1883, one of the ablest of astronomical physicists published an admirable discussion of the corona as a purely subjective, non-material phenomenon, due to the diffraction of the Sun's photospheric rays at the Moon's edge. The objective existence and solar character of the corona are to-day thoroughly established, and the erroneous views of our predecessors come as a surprise no doubt to many persons of the younger generation. It is far otherwise with those who are familiar with eclipse history. Take away the spectroscopic method of study, which came nominally in 1859, but virtually, for eclipse purposes, later in the sixties, and take away the photographic plate which was made to bear upon the problem, faintly in the early seventies and strongly in the eighties,—take these away, and I think we should still be struggling with the question, Where is the corona situated? Let two of us make a pencil drawing of the same corona,—one of us in Spain and the other in Egypt. The two drawings will be more remarkable for their differences than for their agreements; and what is more natural than to attribute these differences to varying conditions in the terrestrial atmosphere above the two observers, or to the changed influence of the irregularities on the Moon's edge as viewed from the two points of observation. Let the eclipse observer of to-day try to find out something new about the corona, *even with* the spectroscope, polariscope, thermoscope, and photographic plate, and his respect for the pioneers will be established upon a firm basis.

The corona remains a strictly eclipse phenomenon. The commendable efforts of several leading astronomers to observe the corona in full sunlight have unfortunately failed, on account of its relative faintness and its low effective temperature, and all the methods now available seem hopelessly unpromising. Given suitable appliances, such as the 40-foot eclipse camera designed by Professor SCHAEBERLE, the corona may be seen faintly and imperfectly during one to three minutes before totality is complete, and during an equal interval after totality ends; but we have not been able to make any scientific use of these pre- and post-totality views. Every item in our knowledge of the corona has been obtained during the total phase. Assuming that observable total eclipses occur, on the average, once in two years, and that their average duration is three minutes, no astronomer, in fifty years of activity in following the Sun and Moon, can hope to utilize more than seventy-five minutes in eclipse observation. Making the reasonable deduction of one third for clouds and other deterring factors, his maximum expectation during a long life must not exceed fifty minutes. The total duration of observable eclipses for any one observer since the spectroscope and photographic plate have been available scarcely equals a half-hour. Herein lies the chief difficulty of coronal investigation. However, the progress made since the spectroscope showed a bright coronal line, in 1869, and photographic plates at two stations showed identical coronal structures, in 1871, has been so great as to be unique in science.

Another difficulty in coronal study is for the most part only vaguely appreciated. The coronal streamers are on the whole radial, with reference to the Sun, and appear to overlie every part of the Sun's spherical surface. Now, every coronal structure lying within the cylinder occulted by the Moon is entirely hidden from view, and all structure lying outside of this cylinder is seen in projection upon one plane. The projected image of the corona recorded on the photographic plate is complex to an apparently hopeless degree. Every small area in the apparent inner corona is a composite of all the structures lying betwen the observer and the area in question. The tops of streamers pointing nearly toward and nearly away from the observer, the intermediate parts of numerous other streamers, and the bases of streamers nearly at right-angles to the observer's line of sight are all projected upon a common area. And similarly for all parts of the coronal image. There is no known way of resolving the composite image into its elements.

Notwithstanding these and other difficulties, we know much concerning the properties and characteristics of the corona. However, this knowledge has not reached the deductive stage. Our facts are isolated ones. We are not only not able to predict the detailed form of a future corona, but we cannot say why an observed corona has a certain general form. We know so little concerning the origin of the corona and its dependence upon the rest of the Sun, that starting *de novo* with our present-day knowledge of the main body of the Sun, and no knowledge whatever of the corona, we should be more surprised by the existence of a corona than by its total absence!

Taking up first the study of coronal images, it has been established that there is a dependence of coronal forms upon the sun-spot period. At and near sun-spot maximum the general outline of the corona is circular. The polar streamers are as extensive and as brilliant as the equatorial streamers. That this is true of the outer regions of the corona as well as of the inner is shown by both long and short photographic exposures. At or near sun-spot minimum the general form is very different. The polar streamers are short, faint, delicate, and few. The equatorial streamers, and especially those in the sun-spot zones or at slightly higher latitudes, are longer than at maximum, and in general there are two broad streamers extending easterly and two westerly from the Sun, several solar diameters in length. These are necessarily but the projections of two sets of long streamers entirely encircling the Sun. Their bases seem to be situated a little further from the equator than are the sun-spot zones. These variations in coronal forms with spot activity are now so well established that coronal streamers and spots may safely be said to have a closely related origin.

The hooded forms of the inner corona, each covering a conspicuous prominence, can leave no doubt that they and the prominences concerned have had a closely related origin.

The great conical disturbance in the corona of 1901, noted by Dr. PERRINE, whose vertex was shown by him to be situated immediately over or very near to the great and only spot on the Sun at the time, can leave little doubt that the disturbed coronal structure and the photospheric disturbance indicated by the spot had a common origin.

All the evidence is to the effect that the corona is closely related to the rest of the Sun. We do not know the nature of this relation; but we can safely say that a thorough understanding of the Sun requires an understanding of the corona.

The light radiated by the corona appears to be of three kinds:—

1st. A thin and very irregular stratum, perhaps never exceeding 200,000 miles, and more probably never exceeding 100,000 miles, in depth, lying at the base of the corona and apparently resting upon the chromosphere, gives a bright-line spectrum. The natural interpretation of this spectrum is that the stratum giving rise to it consists of a gas or vapor heated to incandescence; but it has been suggested here and there that the bright lines may indicate an electric glow in the inner corona, such as one gets from a Plücker tube agitated by an electric current. For my part, there seems to be no real necessity for going beyond simple incandescence produced by the Sun's heat. The element yielding the ten or twelve bright lines[1] has not been identified with any terrestrial substance. There may indeed be more than one vapor or gas present. It is difficult to conceive how irregular masses of vapor can maintain themselves at great heights above the solar surface, in opposition to the Sun's gravitational attraction. Perhaps the vapor is constantly given off by the solid or liquid particles which seem to form the major part of the inner corona, for these particles must be at a high temperature, under the influence of the Sun's heat.

2d. Nearly all of the light from the inner corona—perhaps ninety-five per cent of it—appears to give a strictly continuous spectrum, which indicates a solid or liquid source raised to incandescence. The most reasonable conclusion is that the inner corona consists largely of minute particles maintained at a very high temperature by the adjacent body of the Sun.

3d. The light of the middle and outer corona yields a spectrum which seems to be substantially identical with the solar spectrum—a spectrum containing the usual Fraunhofer dark lines. On this point there is not unanimity of observers. Pluvinel in 1893 and the Crocker Expedition of 1901 to

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[1] Dyson gives a list of twenty-four corona lines.—*Phil. Trans.*, Vol. 206, p. 451, 1906.

Sumatra and of 1905 to Spain have recorded dark lines, whereas others appear to have observed continuous spectrum, pure and simple. The discordance is difficult to explain. If the dark lines exist, we have every reason to believe that the corresponding parts of the corona consist of minute particles of matter, not shining appreciably by their own light, but principally by virtue of original sunlight which radiates to the particles and is reflected and diffracted to us.

The latter view is supported overwhelmingly by a long series of polarization observations. Granted that the corona is composed of minute particles which diffuse the sunlight falling upon them, the coronal light should be polarized, radially, very much as sunlight diffused by our own atmosphere is polarized strongly in planes passing through the Sun. It is true that polarization may be produced otherwise than by reflection or diffusion,—for example, by a magnetic field, as in the Zeeman effect; but polarization seems to exist in all parts of the corona.

The opinions of astronomers as to the materials composing the corona, and as to why the Sun has any corona at all, have been very divergent. Some have believed that the corona is composed of meteors, many of them revolving around the Sun, and others falling into the Sun. However, this theory is largely in disfavor, and we need not consider it, though no doubt there are a great many meteors both revolving around and falling into the Sun.

SCHAEBERLE'S mechanical theory proposes that "the theoretical corona is caused by light emitted and reflected from streams of matter ejected from the Sun by forces which in general act along lines normal to the surface of the Sun, these forces being most active near the center of each sun-spot zone." To account for the longer streamers in the corona, considering their materials to be ejected by forces analogous to volcanic forces and to be drawn back by the Sun's gravitational power, would require that their speeds on leaving the Sun should be between 200 and 400 miles per second. According to this theory, also, there would be multitudes of both ascending and descending particles.

According to BIGELOW'S magnetic theory, the corona is a sort of solar aurora whose streamers occupy positions corresponding to the lines of force in the Sun's magnetic field, just as the Earth's magnetic field seems to control the streamers of terrestrial auroras.

When LEBEDEW, and NICHOLS and HULL, some five or six years ago, proved experimentally that light and heat radiations exert a pressure upon all bodies in their paths, it occurred to ARRHENIUS, and possibly to others, that here is the basis for a satisfactory theory of the corona. If strong radiations press upon exceedingly minute particles, the particles will move away from the source of radiation; the larger and denser particles, speaking popularly, will travel slowly, and the lighter and smaller particles rapidly. There can be little doubt that matter exists at the Sun's surface in a state capable of being acted upon effectively by this radiation pressure. According to this theory, the smaller and lighter particles (more exactly, those having the smallest product of mass and density) would be driven off into distant space, with little chance of returning to the Sun; and the reuniting of two or more particles would in many cases give gravity the advantage, so as to bring them back to the Sun. It is true that this theory, in common with all the others, leaves much to be explained. For example, it is difficult to say why sun-spot inactivity should produce extraordinarily long streamers in the high sun-spot latitudes, and sun-spot activity streamers of equal lengths all over the Sun.

I think there is an excellent chance that all these theories have much truth in them. There can be no question that eruptive forces, or convection and evection currents of great speed, exist at the Sun's surface,—responsible for many of the prominences, certainly,—and perhaps they give an outward impulse to the coronal material. The forms of many coronal streamers certainly resemble closely the lines of force in a magnetic field, and we cannot doubt that radiation pressure must be active and effective. But it is scarcely conceivable that the eruptive forces on the Sun can give speeds of 300 or 400 miles per second to the ejected coronal materials, and the radiation-pressure theory renders the supposition of such great speeds unnecessary.

At the eclipse of 1900, ABBOT made one of the most important of recent eclipse observations, in that he measured the heat radiation of the inner corona. He found that the corona is effectively cooler than the instrument with which he observed. The observation was a delicate one and liable to considerable error. Although confirmation is very urgently desired, ABBOT'S observation is probably approximately correct. ABBOT concluded that the corona appears "neither to reflect much light from the Sun nor chiefly by virtue of a high temperature to give light of its own, but seems rather to be giving light in a manner not associated with a high temperature. . . ." This conclusion seemed at first to deny the theory of the corona's constitution outlined above, as based upon the evidence of the spectroscope and polariscope; but a very illuminating paper by ARRHENIUS has, I think, shown that ABBOT'S results on the heat of the corona are in harmony with the view that the inner corona consists mainly of incandescent particles.

ARRHENIUS has determined from computation that coronal particles in the region observed by ABBOT must have a temperature of about 4,300° C. (8,000° F.), assuming the effective temperature of the Sun's photosphere to be 6,000° C.; and, therefore, these particles must be radiating light by virtue of their own incandescence. These particles are so few and so far apart that the effective temperature observed by the bolometer is not at all the temperature of the particles themselves, but is, so to speak, the average temperature for the incandescent particles and the cold background of space upon which these particles are seen here and there in projection. The total area of the background covered by the particles in projection is an exceedingly minute fraction of the whole area. The spectroscopic and thermometric observations are harmonized within the limits of error of observation by assuming that, in the part of the corona observed, there is but one minute dust-particle for each fifteen cubic yards of space.

We should not overlook the fact that the series of incandescent points in the distant corona affect the eye or the photographic plate just as if they formed a continuous and highly illuminated surface, whereas the thermometer in effect averages the radiations from the coronal particles to the instrument and the radiations from the instrument to the cold background of space. The action of our atmosphere in stopping a certain proportion of the heat radiations is also effective and has to be taken into account.

The existence of matter in the corona at great distances from the Sun implies that it has come from somewhere—doubtless from the Sun itself. This necessarily implies that motion has occurred. Is the material of the corona moving out from the Sun or toward the Sun, or both, or neither? We have no accurate observational knowledge on this subject. The unusually favorable eclipse of August 30, 1905, offered a hope that large-scale photographs of the corona secured in Labrador, Spain, and Egypt, or in two of these countries, would enable us to detect changes in the coronal structure occurring between the instants of totality in those countries. Dr. PERRINE and I have made careful comparisons of the coronal images recorded by the Crocker Eclipse Expeditions in Spain and Egypt. A number of fairly well-defined nuclei of the corona existed both east and west of the Sun. As a result of these comparisons we are able to say that there is no certain evidence of motion having occurred in the interval of 70 minutes which elapsed between the instants of totality in Spain and Egypt. Details of structure within the nuclei have suffered change, but the mass as a whole cannot have moved so much as one mile per second during the interval. Greater speeds might well have occurred in the principal coronal streamers without our having detected them; for their structure is uniform and regular, and well-defined nuclei are absent. Thus, in the cases where high speeds should perhaps be most naturally expected, photographic plates have little power to record them.

Measures of motions of approach and recession within the corona by means of the spectrograph are unpromising, for several reasons. The coronal light is intrinsically weak, and exposures are from necessity short. The brighter parts of the corona radiate light forming a continuous spectrum, neglecting the almost insignificant component which gives rise to bright lines. Even if spectrograms of the middle and outer coronal regions could be secured with the Fraunhofer lines recorded in good strength, their interpretation would be difficult and somewhat unpromising. The slit of the spectrograph would receive light from streamers which radiate in a variety of directions from the Sun. There would be streamers pointing both toward and away from the observer and streamers occupying positions of all values intermediate between these limits. If the coronal particles were moving outward exclusively, the general effect would be to cause a shift corresponding to recession, but the lines would be broadened. Particles moving toward the Sun would in effect displace in the direction of approach, at the same time broadening the lines. It will be easy for the reader to determine the effect of a motion of either kind in a streamer making a given angle with the observer's line of sight, and space will not be taken here to summarize further the general effect. It is evident that a dark-line spectrum, if one of sufficient density and dispersion could be obtained, would be of great complexity. However, a knowledge of the motions within the corona would doubtless be our most effective power in determining the origin of the corona, and the subject should not be abandoned as hopeless.

PLANETARY PHENOMENA FOR MAY AND JUNE, 1907.

By Malcolm McNeill.

PHASES OF THE MOON, PACIFIC TIME.

Last Quarter..	May 4,	$1^h 53^m$ P.M.	Last Quarter..	June 2,	$9^h 20^m$ P.M.
New Moon....	" 12,	12 59 A.M.	New Moon....	" 10,	3 50 P.M.
First Quarter..	" 20,	5 27 A.M.	First Quarter..	" 18,	6 55 P.M.
Full Moon....	" 27,	6 18 A.M.	Full Moon....	" 25,	1 27 P.M.

The summer solstice, the time when the Sun stops moving north and begins to move south, occurs June 22d, 6 A.M., Pacific time.

Mercury is a morning star on May 1st, rising less than an hour before sunrise, and is therefore too near the Sun for naked-eye observation. It moves rapidly toward the Sun, and passes superior conjunction, becoming an evening star, on the night of May 23d-24th. It then moves rapidly away from the Sun and a little northward. Shortly after June 1st it remains above the horizon an hour after sunset, and this period increases to about an hour and three quarters soon after the middle of the month. It then begins to shorten, but does not go below an hour and one half until after the close of the month. Greatest east elongation (25° 29′) is reached on June 27th. This is not quite the maximum possible, but is not much below it. The month of June this year therefore